esi® Engineering Bulletin

Electro Scientific Industries

13900 N.W. SCIENCE PARK DRIVE • PORTLAND, OREGON 97229

GENERAL

no. 42

MAY 1964

SYSTEMETRICS, A NEW CONCEPT IN ELECTRICAL MEASUREMENTS

by

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SYSTEMETRICS, A NEW CONCEPT IN ELECTRICAL MEASUREMENTS

THE NEED FOR BETTER MEASUREMENTS

Accurate measurement is the cornerstone of modern science and technology. As the probing of the laws of nature becomes more exacting, substantial advances must be made in metrology to validate new discoveries. As this new knowledge is reduced to practice, accurate measurement moves out of the research laboratory and becomes indispensable to the success of industrial and government projects based on the new technology.

TRACEABILITY

The need for more accurate measurement has been most evident in establishing traceability and determining reliability. Traceability links working measurements with maximum accuracy to the values of the units that are maintained by the NBS. Thus everyone uses the same measurement base so that devices made by different firms will work together. Traceability maintains consistent measurements so that the same quantity measured by different techniques will be assigned the same value.

RELIABILITY

One of the major areas in reliability determination is proving that the rate of change (stability) of component values is less than a specified amount. The average rate of change of a component in a given time is the ratio of two numbers, the amount of change and the length of time. Any lack of measurement repeatability will appear as an uncertainty in the determination of the amount of component change. Measurement repeatability (precision) is directly related to the amount of time needed to show that the rate of change of a component's value is less than a specified amount. Figure 1 shows this relationship. Better measurement repeatability means less time to establish stability.

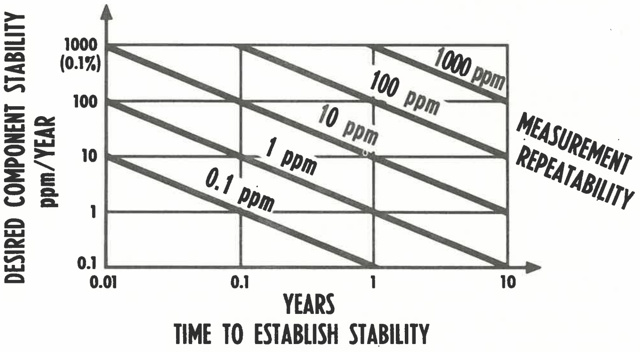


FIGURE 1. TIME AND STABILITY

When better measurements are to be used to reduce the time required to establish component stability, it must be assumed that the rate of change of component value will not increase. This is a reasonable assumption for high-quality passive precision components. The same assumption is always made when suitability for use is being determined. Also, better measurements can lower the stresses of accelerated aging and reduce the possibility of failures induced by testing.

If the value of a component meanders, the meandering cannot be found unless it is greater than the measurement repeatability; another reason for making better measurements.

The term "measurement repeatability" has been used because it, and not "accuracy", is needed to measure stability. Measurements must be repeatable relative to a stable measurement base, but the measurement base does not have to be accurate. In stability measurements, systematic errors in tracing to the measurement base are much less important than random errors. Even so, it is a good idea to use measurements that are traceable to the National Bureau of Standards and have low systematic and random errors. Such measurements ensure reproducible results because the National Bureau of Standards can provide the most stable measurement base available.

SYSTEMETRICS

To meet the need for more precise measurements, ESI has dedicated its continuing effort to a measurement concept that integrates all of the factors needed in a coordinated measurement system. We call this concept "Systemetrics". Its fundamental purpose is the maximum extraction of data from nature with maximum accuracy and minimum effort.

This approach to electrical calibration resulted in the selection of ESI equipment and techniques by the United States Air Force within the past two years to upgrade the capabilities of their Precision Measurement Equipment Laboratories.

THE CHARACTERISTICS OF SYSTEMETRICS

As it is envisioned by ESI, Systemetrics has three major characteristics. The first characteristic is measurement systems. Each kind of measurement is made with a system; a semi-permanently connected group of matched or complimentary instruments, or one instrument. Each system is used to make measurements with advanced metrology techniques. The second characteristic is on-the-spot calibration. The systems are calibrated in their working environment with equipment and techniques that use a minimum number of transportable reference standards. Measurement traceability is established in this way with minimum transportation errors. The third characteristic of Systemetrics is ergonomic instrument design. Ergonomics is a study of the relationship between man and his working environment and it is the application of his physiological and psychological knowledge for the improvement of this relationship.

ADVANTAGES OF SYSTEMETRICS

An alternative to Systemetrics is to gather together the several pieces of equipment, connect them in an appropriate manner, and then proceed with the measurement. If a system is designed to cover a broad range of values, it probably will not make an optimum measurement at every value and it may be possible to assemble equipment which will out-perform the system in some specific situation. However, a system will perform most desired measurements satisfactorily, and will certainly be faster, easier to use, and require much less operator training.

EXAMPLES OF SYSTEMETRICS DESIGN

In order to demonstrate the practical application of the principles of Systemetrics, some engineering details in four ESI systems will be discussed; a resistance measurement system, a dc voltage and ratio calibration system, an ac ratio system, and a capacitance measurement system.

MODEL 242 RESISTANCE MEASURING SYSTEM

The ESI Model 242 Kelvin Resistance System measures values from a fraction of an ohm to 120 megohms with accuracies of 50 ppm or 100 ppm over most of this range. It is shown in Figure 2. The system is composed of three instruments: the

Model 240 Kelvin Ratio Bridge, the Model RS 925A Decade Resistance Standard and the Model 800 Generator-Detector.

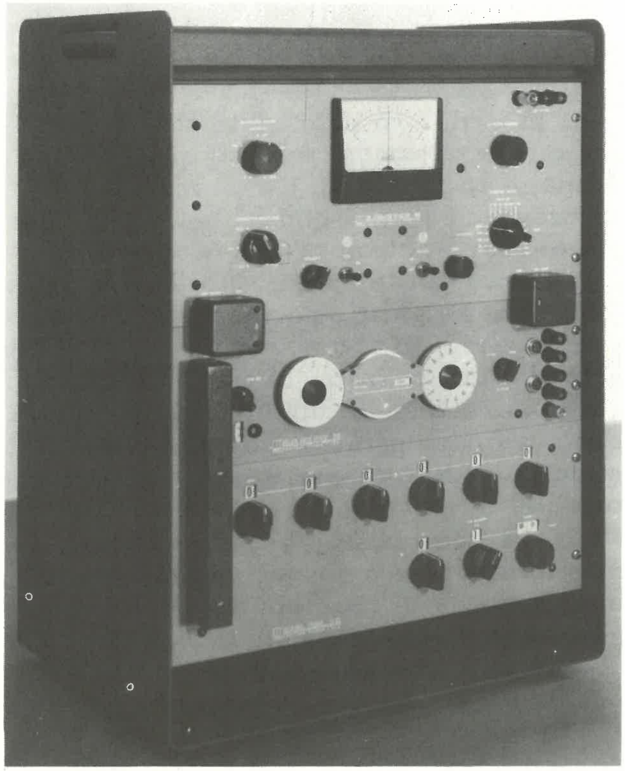


FIGURE 2. KELVIN RESISTANCE SYSTEM

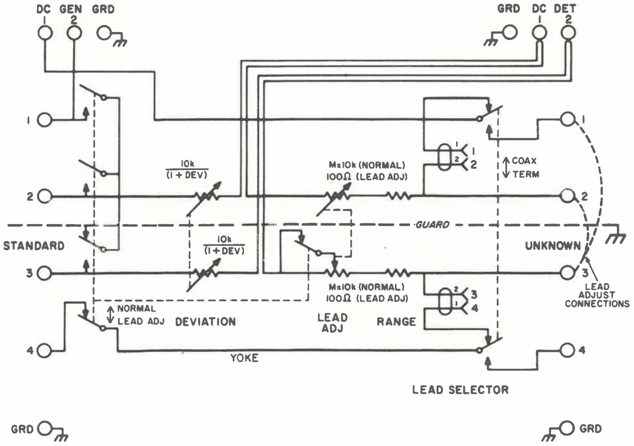


FIGURE 3. KELVIN BRIDGE SCHEMATIC

MODEL 240 KELVIN RATIO BRIDGE

A simplified schematic of the Model 240 Kelvin Ratio Bridge is shown in Figure 3. The Kelvin Ratio Bridge compares a standard resistor to an unknown resistor which may have a value 100, 10, 1, 0.1 or 0.01 times the value of the standard resistor. These ratios extend the range of the decade resistance standard and reduce the effect of any lead or contact resistances in the decade resistance standard. The deviation dial, which has 1 ppm resolution, changes the ratios from their nominal value so that the unknown resistor may be read in terms of deviation in ppm from the value of a decade resistance standard. One feature of this instrument is four-terminal connections as well as guarding. This feature allows the instrument to be used over a very wide range of values because four-terminal connection reduces contact resistance effects in low resistance measurements, and guarding reduces leakage problems in high resistance measurements. The main and auxiliary ratio arms of the bridge are guarded by the chassis of the instrument so that leakage resistances in the ratio set do not shunt the unknown or standard resistors. The deviation dial, when used in conjunction with the Model RS 925A Decade Resistance Standard, allows the operator to correct the bridge to agree with a standard and then read the correct value of the unknown resistor, either in terms of ohms or in terms of ppm deviation from a nominal value. This feature eliminates the need for separate calculations, greatly reduces operator effort, and minimizes the possibility of errors.

MODEL RS 925A DECADE RESISTANCE STANDARD

A simplified schematic of the Model RS 925A Decade Resistance Standard is shown in Figure 4. This instrument has four-terminal connections at the ends of the decade, which allows the incorporation of many unique features. In an ordinary decade resistor, contact resistance would make the 10.5-milliohm rheostat practically useless. In the Model RS 925A, the contact resistance appears in series with the bridge generator, where it will have no effect, and the setting of the rheostat is repeatable to better than 0.1 milliohms.

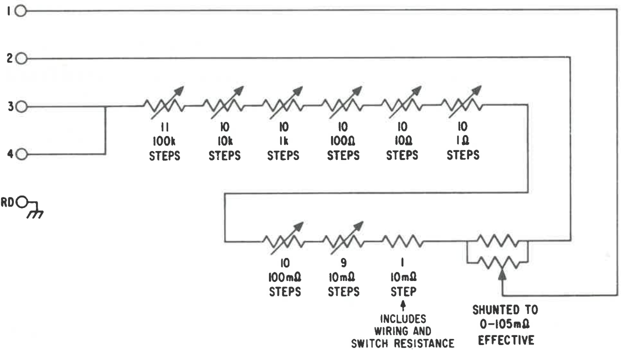
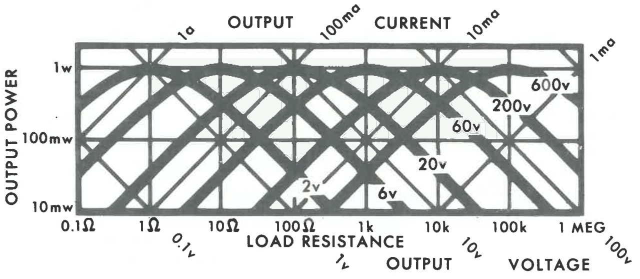


FIGURE 4. DECADE RESISTANCE STANDARD SCHEMATIC

The unused portion of the rheostat resistance is in series with a 10-kilohm bridge arm where it will not change the bridge ratio by more than 1 ppm. Since the leads connected to the RS 925A do not appear as part of its resistance, the 10-milliohm-per-step dial starts reading at 1, and the lead and contact resistance in the instrument have been adjusted to equal 10 milliohms, the dials of the instrument indicate the resistance at the terminals without any correction for zero resistance, as would be required in an ordinary decade resistor. The 10-milliohm-per-step dial cannot be set at zero, thus a resistance value such as 1,000 ohms must be set on the dials as 999.9(TEN)00 ohms. The use of nines instead of zeros dissipates the power in the Model RS 925A over a much larger number of resistors and reduces the power coefficient of the instrument. All of the decades use multiple contact silver alloy switches. The average repeatability of the 10 milliohm setting (the minimum setting) is less than 50 microhms. These features of the Model 925A Decade Resistance Standard increase the accuracy of precision measurements and reduce the effort required to obtain them.

MODEL 800 GENERATOR-DETECTOR

In order to eliminate the possibility of overheating causing permanent damage to the Model 242 or to an unknown resistor connected to it, the generator section of the Model 800 Generator-Detector is power-limited. The power-limiting level is continuously variable from 0 to 1 watt, which allows the operator of the instrument to be sure that an unknown resistor is not dissipating more power than it should. The power limiting is accomplished by putting a resistor in series with the generator voltage. Since maximum power is delivered with a specific resistance connected to the generator terminals (matched-load condition), the generator has six output ranges. Nearly maximum power is available over a wide range of load resistances, which maintains maximum bridge sensitivity over a wide range of resistance. Figure 5 shows the generator output power curves of the Model 800. Figure 6 shows a bridge connected to a power-limited generator.



MAXIMUM OUTPUT OF THE MODEL 800 GENERATOR

FIGURE 5. GENERATOR OUTPUT

A power-limited generator must be well guarded. The effect of the leakage resistances from the bridge corners to ground is well understood, but it is not generally realized that the leakage resistance from ground to the junction between the generator resistance and the battery will have a serious effect on the bridge accuracy.

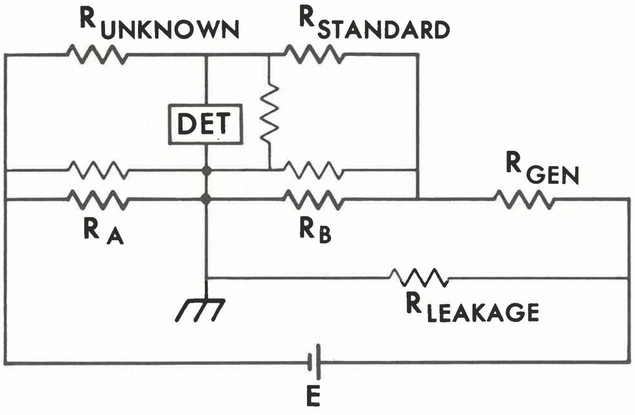


FIGURE 6. LEAKAGE RESISTANCE

The effect is magnified by the presence of the generator (power limiting) resistance. Figure 7 shows how a fraction of this leakage resistance is, in effect, connected across the bridge ratio arm R_B. This is worse than having the whole leakage resistance connected across R_B, and the error will increase as the generator resistance becomes larger compared to the bridge resistances. However, if the generator circuit is guarded, as shown in Figure 8, the leakage problem will be eliminated.

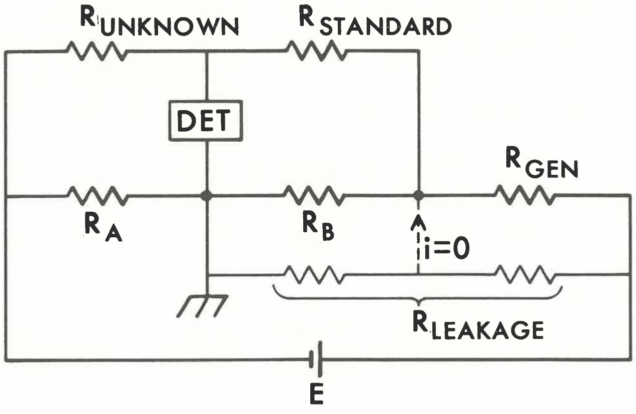


FIGURE 7. EQUIVALENT GENERATOR LEAKAGE

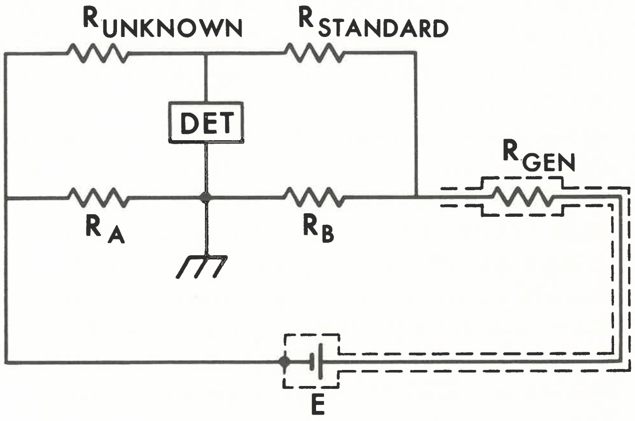


FIGURE 8. GUARDED GENERATOR

Figure 9 is a simplified schematic of the Model 800 Generator-Detector showing the guarded generator. The timing switch shown in the schematic shorts the detector momentarily while the generator is turned on and off. This isolates the detector from momentary capacitive or inductive transients appearing in the bridge circuit. Shorting the detector in this way results in much better detector operation.

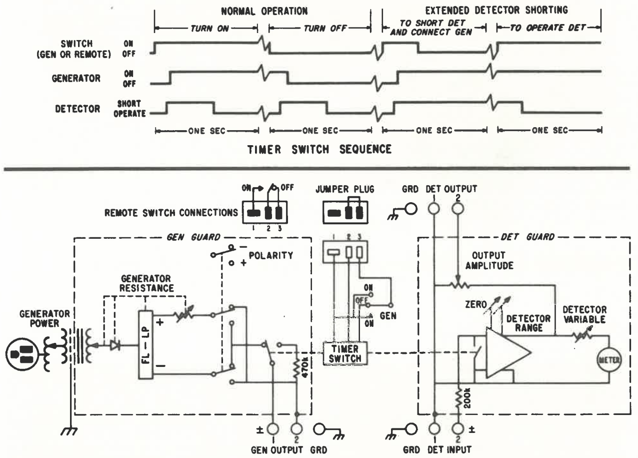


FIGURE 9. GENERATOR-DETECTOR SCHEMATIC

AUTOMATIC DATA LOGGING

Human instrument operators are very good at repeated null balancing and at recognizing changes or deviations from normal operation (i.e. - such things as thermals, noise, overheating, etc.), but they are not as efficient as machines at writing down or mathematically manipulating results. In order to take advantage of developments in data processing, many ESI systems are available with automatic data logging. These systems offer the user the advantage of machine handled data, free the operators to do those things at which they are best, and result in more precise measurements than can be obtained from available fully automatic dequipment. Figure 10 shows an ESI system with automatic data logging equipment.

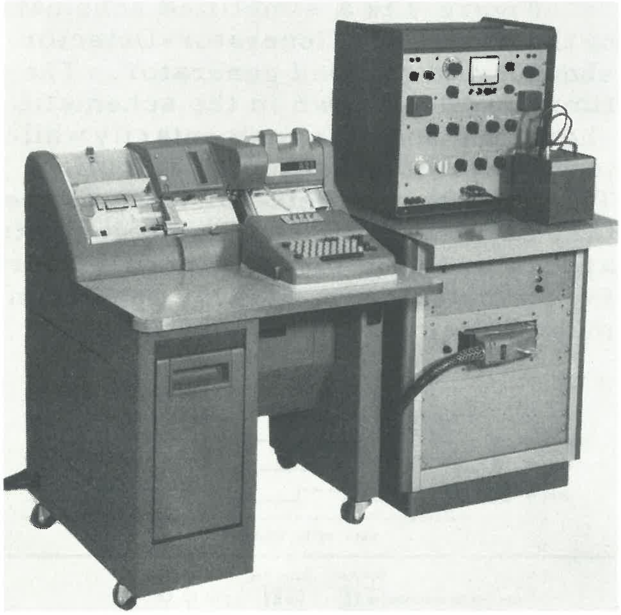


FIGURE 10. AUTOMATIC DATA RECORDING

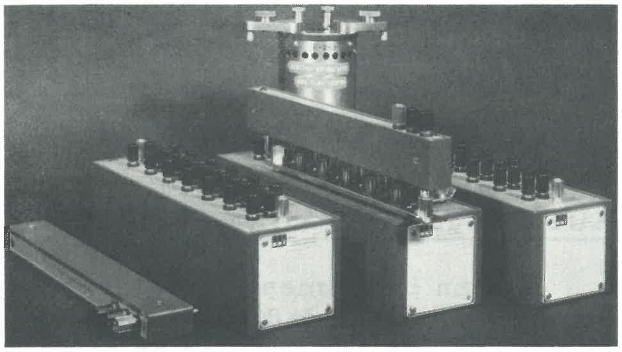


FIGURE 11. STANDARD RESISTOR AND TRANSFER RESISTANCE BOXES

MODEL SR 1010 TRANSFER RESISTANCE BOXES

The Model SR 1010 Transfer Resistance Boxes shown in Figure 11 are used to transfer from an NBS calibrated resistor to other resistance values. They are used to calibrate the Model 242 Kelvin Resistance System in its working environment and can also be used to calibrate attenuators and voltage dividers. The Model SR 1010 is unique in that it consists of four-terminal resistors that can be connected in series or parallel combinations within ± 1 ppm precision, even at the one-ohm-per-resistor level.

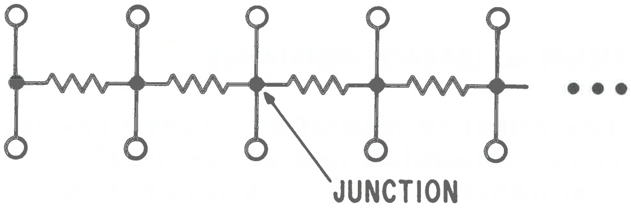


FIGURE 12. TRANSFER RESISTANCE BOX SCHEMATIC

A schematic of a transfer resistance box is shown in Figure 12. The four-terminal resistors can be measured individually or in any series combination. If the measured series resistance is to be equal to the sum of the individual resistor measurements, or if parallel connections are to be made accurately, the junctions must have zero four-terminal resistance. The junction resistance is zero if a current source connected to any two of

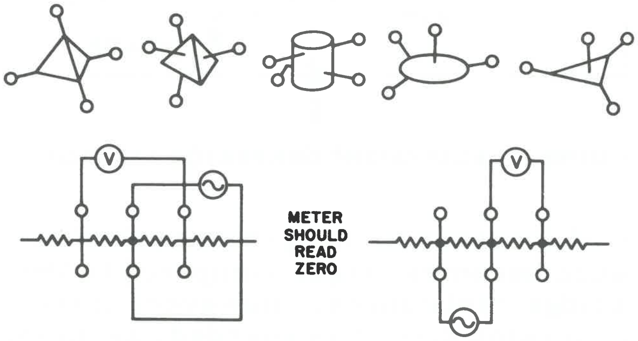


FIGURE 13. ZERO-RESISTANCE JUNCTIONS

the four junction terminals produces zero voltage between the other two terminals.

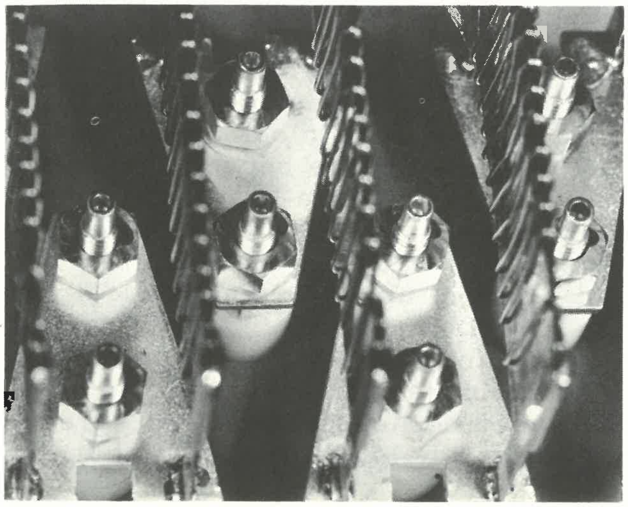


FIGURE 14. TRANSFER RESISTANCE BOX JUNCTIONS

If four terminals are connected to a plain sheet of metal in the configuration shown in Figure 13, two of the terminals will always be on an equipotential line when a current source is connected to the other two terminals. In practice, such junctions do have some resistance but the resistance is very low (much less than 1 microhm). The actual terminals, shown in Figure 14, are a simple modification of this equilateral triangle situation. Their actual four-terminal resistances are less than 1/2 microhm which is equivalent to the resistance of about 0.001 inches of number 18 copper wire.

MODEL 701 CAPACITANCE MEASURING SYSTEM

The ESI Model 701 Capacitance Measuring System and the Model SC 1000 Standard Capacitor which is used to calibrate this system are shown in Figure 15. In addition to such features as a continuously-variable ganged generator and detector frequency control, the Model 701 Capacitance System has many features in common with the Model 242 Resistance System. Some of these features are separate value and deviation dials, 1 ppm resolution, traceable calibration using ratios, a stable transportable standard which is calibrated by the NBS, and ergonomic design.

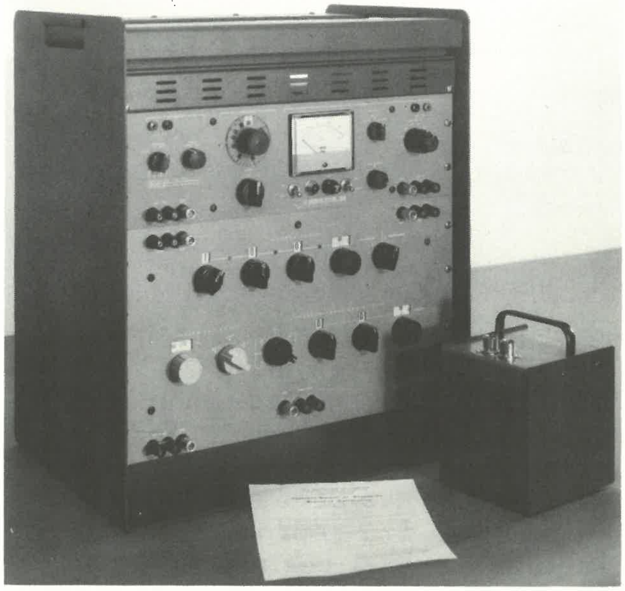


FIGURE 15. STANDARD CAPACITOR AND CAPACITANCE MEASURING SYSTEM

The Model 701 Capacitance Measuring System has one big advantage over resistance-measuring systems; it uses transformer ratios that are relatively independent of instrument environment and time. Once transformer ratios have been calibrated, it is necessary only to check the single standard capacitor in the bridge (using the Model SC 1000 Standard Capacitor) to calibrate the whole system. Since it requires only one measurement to check the bridge and since the bridge is available with automatic data logging, the Model 701 is particularly useful and easy to use in reliability and stability work.

A simplified schematic of the bridge used in the Model 701 Capacitance Measuring System is shown in Figure 16. The bridge and the leads supplied with it are shielded so that there is no need to compensate for zero capacitance. The deviation dials, which have 1-ppm-per-dial-division resolution, permit the operator to express the value of unknown capacitors directly in capacitance or in terms of ppm deviation from a nominal value of capacitance.

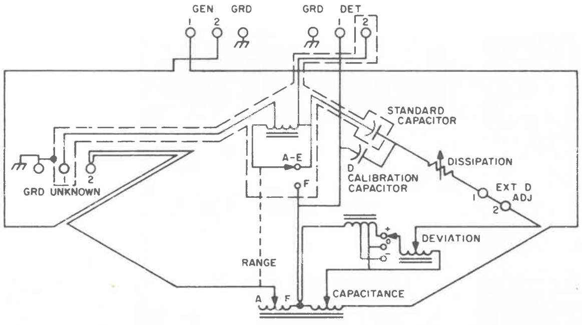


FIGURE 16. CAPACITANCE BRIDGE SCHEMATIC

The front panel of the capacitance bridge is shown in Figure 17. The last capacitance dial is continuously variable and has zero and full-scale settings that are reproducible to a fraction of a part per million, allowing the operator to use the deviation dials to obtain capacitance readings with greater than six-place resolution.

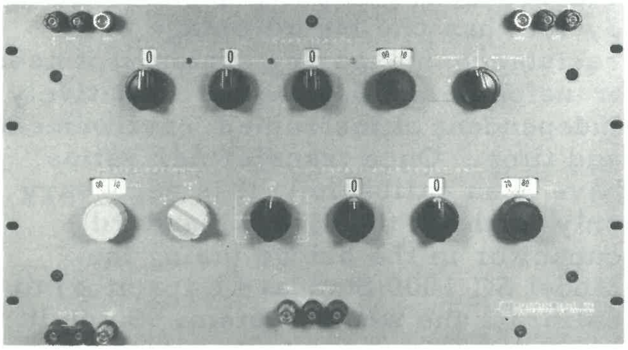


FIGURE 17. CAPACITANCE BRIDGE

ESI DIALS AND KNOBS

Since dials have just been mentioned, it is worth while to point out features of ESI-designed dials that simplify setting and reading dials and speed accurate bridge balancing. Most ESI-designed dials are continuously rotatable so that they can be turned directly from nine or ten to zero. Where possible, the detent between these settings is left out so that the dials will not be left in a meaningless position. Bar knobs on ESI dials are set to clock positions; 1 is at one o'clock, 2 at two o'clock and so on. The correspondence between numbers and clock positions allows dials to be set with a minimum of visual attention. The additional positions of - 1 and TEN are added to dials where possible so that bridge balance can be speeded and comparison accuracy can often be increased. Accuracy is increased because changes of more significant dials, which contribute larger errors, can be avoided. Another ESI innovation is rheostat dials that have geared-down reversing drives which permit in-line readings, easier setability, clockwise rotation for increased reading, and dial scales which read from left to right.

MODEL 731 DC RATIO AND VOLTAGE CALIBRATION SYSTEM

The ESI Model 731 DC Ratio and Voltage Calibration System is shown in Figure 18. If a dc voltage calibration system is to be used for a wide variety of measurements (such as digital voltmeter calibration or volt box calibrations), it is desirable for it to have a highly-accurate low-impedance voltage source - i.e. an accurate power supply. However, the accuracy of available power supplies is of the same order of magnitude as some of the devices that need calibration. When the ESI Model PC 1040 Guarded Potentiometric Calibrator and Model RV 722 Kelvin-Varley Voltage Divider are used with a stable voltage source, the voltage can be calibrated to accuracies approaching 10 ppm. When the ESI Model LC 875A Lead Corrector is added to complete the Model 731 system, the system can be used to calibrate volt boxes and attenuators operating at their rated voltages, and to calibrate Kelvin-Varley voltage dividers.

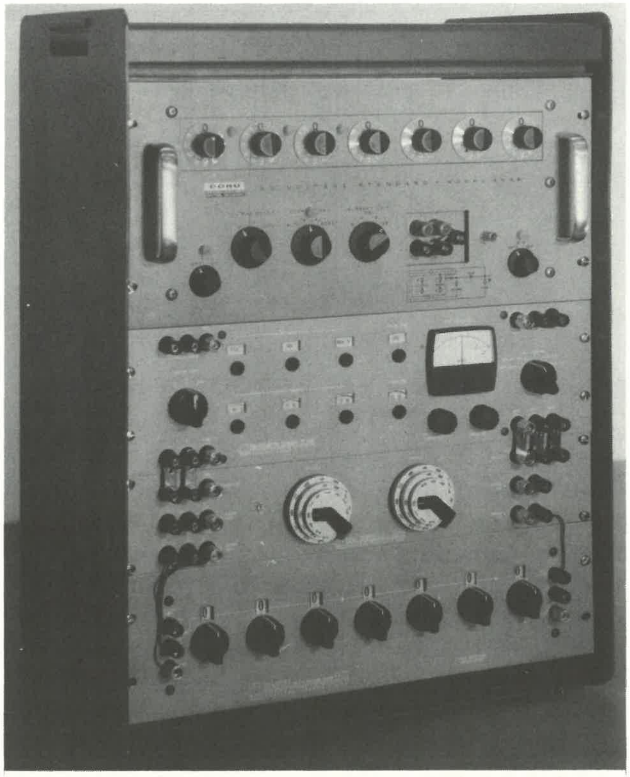


FIGURE 18. DC RATIO AND VOLTAGE CALIBRATION SYSTEM

The lead corrector is a very convenient device that balances lead resistances so that dividers can be made to agree at zero and full scale settings. With this system, the calibration of a voltage source can be monitored relative to a bank of saturated standard cells while the voltage source is being used to check another device.

MODEL PC 1040 GUARDED POTENTIOMETRIC CALIBRATOR

A simplified schematic of the Model PC 1040 is shown in Figure 19. The Model PC 1040 is a guarded absolute ratio self-calibrating volt box with a battery operated guarded null detector. The volt box is designed to operate up to 1200 volts. The null detector is completely floating and can be driven to 1200 volts above chassis ground without errors from stray leakage currents. There will be no damage to the input of the detector if the entire 1200 volts is applied inadvertently to the input terminals.

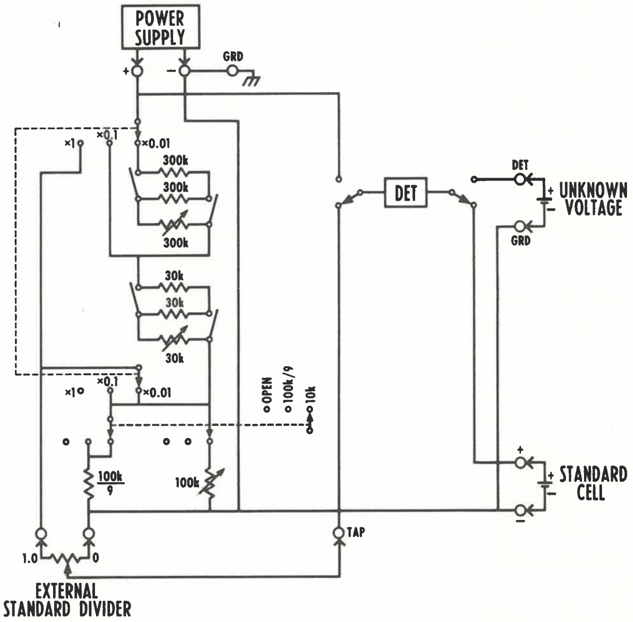


FIGURE 19. POTENTIOMETRIC CALIBRATOR SCHEMATIC

The bottom section of the voltage divider (volt box) has a nominal value of 10,000 ohms. The instrument is designed so that the 100,000-ohm input resistance of a Kelvin-Varley divider, such as the Model RV 722 which is attached to the Model PC 1040, can form part of this 10,000 ohms. The null detector can be used to compare points on the voltage divider or the output of the Kelvin-Varley voltage divider to a reference voltage in order to calibrate the dc voltage standard. Notice that the 90k and the 900k sections of the voltage divider string of the Model PC 1040 is each made up of three nominally-equal resistance sections, one of which is adjustable. Self-calibration of the instrument is accomplished by connecting the three nominally-equal resistors of each section in parallel, comparing them to the part of the divider that is immediately below them. The adjustable resistors are trimmed so that the parts of the divider are within 1 ppm of equality. The parts of the divider are compared by an interchange technique with the ratio test arms that are part of the instrument. Figure 20 shows one part of the calibration procedure. The self-calibration procedure can be accomplished in a few minutes without removing the instrument from its rack and without making any connections. This technique permits the operator to accomplish a complete calibration quickly whenever it is desired. The voltage divider of the Model PC 1040 is guarded by a separate guard drive divider to minimize insulation resistance problems in the instrument.

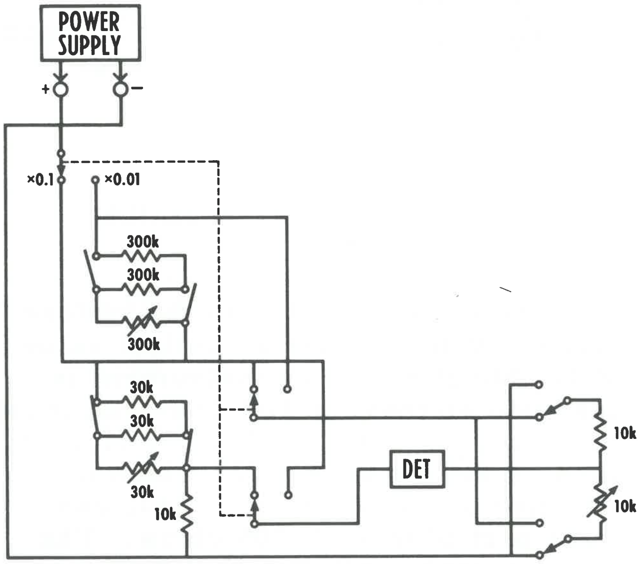
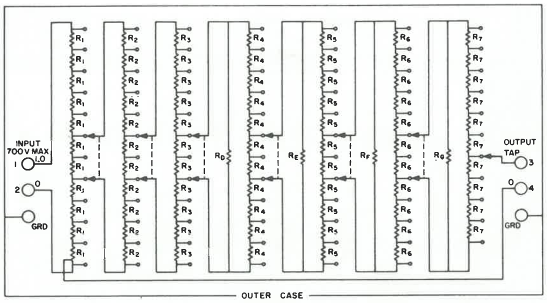


FIGURE 20. CALIBRATION PROCEDURE

MODEL RV 722 KELVIN-VARLEY VOLTAGE DIVIDER

A schematic of the ESI Model RV 722 Kelvin-Varley Voltage Divider is shown in Figure 21. This instrument was the first 7-dial Kelvin-Varley voltage divider available on the market. The divider has 1 ppm linearity and the linearity improves considerably as the instrument is operated at lower and lower settings; with the first few dials on zero.



R_1	R_2	R_3	R_D	R_4	R_E	R_5	R_F	R_6	R_G	R_7
10k	2k	400Ω	1k	400Ω	1k	400Ω	1k	400Ω	1k	400Ω

FIGURE 21. KELVIN-VARLEY VOLTAGE DIVIDER SCHEMATIC

The Model RV 722 can be used as an accurate voltage ratio device because of the compensated output common connection. A normal Kelvin-Varley output voltage will not be zero when all of the dials are set to zero because of end effects, stray switch and lead resistances. This output voltage error becomes a larger percentage of the output as the voltage division ratio gets smaller. The Model RV 722 has a compensated common output terminal which supplies a voltage equal to the output tap voltage when all of the dials are on zero. Because switch contact resistance varies (a few tenths of a milliohm), this compensation cannot be perfect, but the voltage between the output tap and the output common will be less than 0.002 ppm of the input voltage when all of the dials are on zero. The result is a voltage division accuracy at very low settings that is more than ten times better than a normal Kelvin-Varley voltage divider of the same input resistance.

Another feature of the Model RV 722 is auxiliary input terminals at each decade. The auxiliary input terminals permit a calibration procedure that was developed by two ESI engineers. It is a calibration technique that uses the necessary and sufficient measurements to find the linearity deviation of a Kelvin-Varley voltage divider at any setting.

TWO AC RATIO SYSTEMS

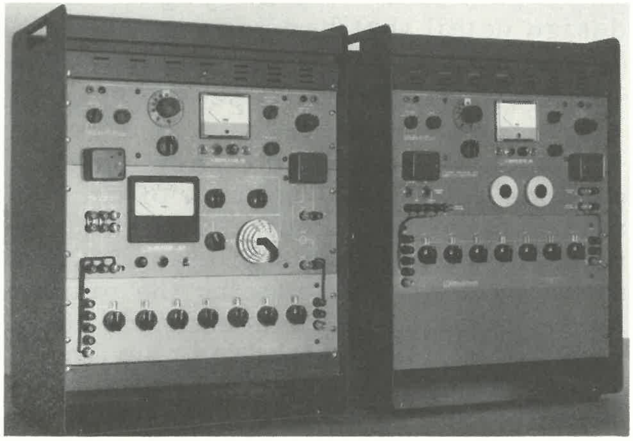


FIGURE 22. AC RATIO SYSTEMS

Two ESI ac ratio systems are shown in Figure 22. Both of these systems use the Model 861A AC Generator-Detector which is also used in the Model 701 Capacitance Measuring System and both use the Model DT 72A Decade Transformer. The Model 1071 system uses the Model 874 Phase Corrector, and the Model 791 system uses the Model RA 79 AC Ratio Accessory for phase correction.

MODEL DT 72A DECADE TRANSFORMER DIVIDER

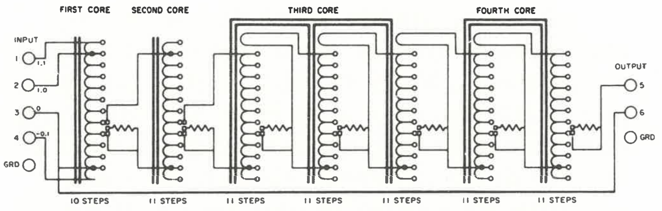


FIGURE 23. DECADE TRANSFORMER DIVIDER SCHEMATIC

A simplified schematic of the ESI Model DT 72A Decade Transformer Divider is shown in Figure 23. This instrument was the first decade transformer divider on the market to incorporate 7-place resolution, -0.1 and +1.1 taps at the input, and -1 positions on the individual decades. The circuit uses separate toroidal cores in a manner that results in negligible linearity change when the same setting is provided by different dial combinations; such as 0.1000000 and 0.099999(TEN).

It is not necessary to calibrate the Model DT 72A in its working environment because transformers are inherently stable. The best calibration procedure is to send the unit to the NBS, or compare it to an NBS-calibrated decade transformer. It is possible to check the unit to better than 1/2 ppm accuracy by using a Model SR 1010 Resistance Transfer Standard.

MODEL 874 PHASE CORRECTOR

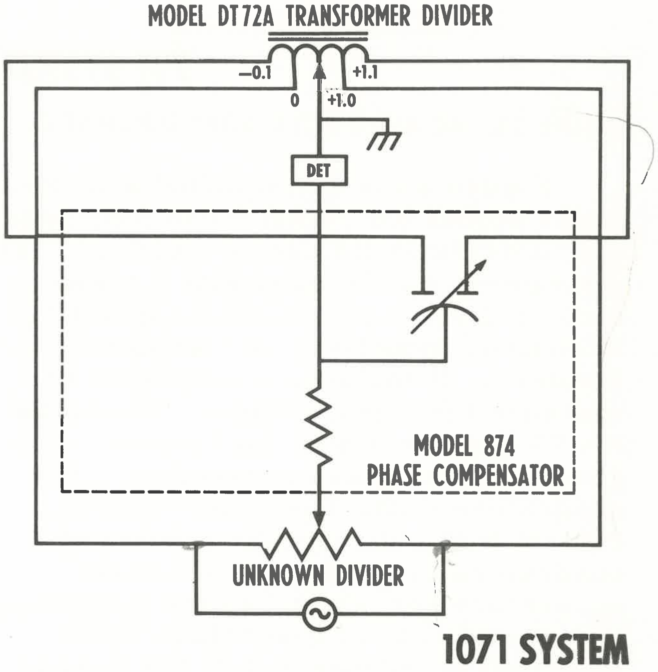


FIGURE 24. PHASE CORRECTOR SCHEMATIC

Figure 24 shows a schematic of Model 874 Phase Corrector that illustrates its use in a circuit. The Model 874 can be used in callibration of resistive or transformer dividers. It causes no degradation in the accuracy of the measurement of the in-phase component, but it gives no indication of the amount of quadrature insertion.

MODEL RA 79 AC RATIO ACCESSORY

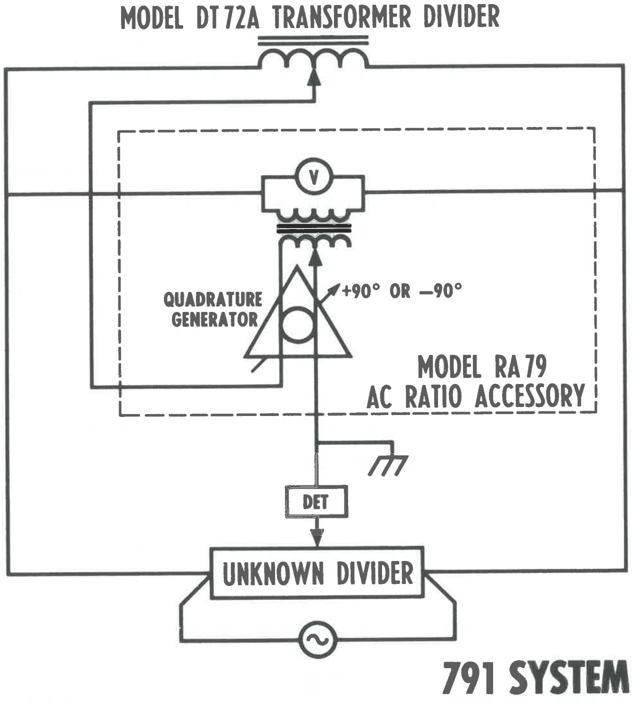

MODEL DT72A TRANSFORMER DIVIDER
V
QUADRATURE GENERATOR
+90° OR −90°
MODEL RA 79 AC RATIO ACCESSORY
DET
UNKNOWN DIVIDER
791 SYSTEM

FIGURE 25. AC RATIO ACCESSORY SCHEMATIC

Figure 25 is a simplified schematic of the Model RA 79 AC Ratio Accessory that illustrates its use in a circuit. The instrument can be used with a transformer divider to measure capacitive, resistive, inductive, or transformer dividers. It includes a voltmeter to measure the input voltage. The Model RA 79 uses an active quadrature generator for phase correction. The quadrature control is a five-decade control that indicates the amount of quadrature insertion. The active quadrature generator has the advantage that the amount of quadrature ratio insertion is independent of the impedances and settings of the dividers being compared. For this reason, less dial turning is necessary in practical measurement situations. The Model RA 79 AC Ratio Accessory will accomplish many measurements that cannot be done with a simple differential capacitor phase shifter.

CONCLUSION

The purpose of this paper is to present some of the concepts that can facilitate a systematic approach to electrical measurements. The preceding information has covered only a small part of the engineering and design detail that has gone into the ESI Systemetric approach to precision dc and audio frequency measurements.

Such concepts and equipment can produce substantial savings of time and money in meeting contractual requirements for traceability of electrical measurements by reducing the primary NBS calibrated reference standards required to just a standard ohm, a standard volt, and a standard nanofarad capacitor. The ability to calibrate the remaining equipment precisely and quickly against these primary reference standards greatly shortens the calibration chain and eliminates a substantial amount of human and equipment error. These calibrations can be done directly at the working equipment site to further reduce the logistic problem of moving large amounts of equipment between the actual working test site and higher echelon calibration laboratories. With the ESI Systemetric approach, traceability of measurement can be established with maximum accuracy from a minimum number of NBS calibrated reference standards and extrapolated accurately over a broad working range of measurements.

A very stable base for working measurements is also provided by such a system. With stability of a few parts per million over a period of many years now possible at the working measurement level, drift rates of electrical components or systems can be verified in a very short observation period. For example, it is possible to verify 0.1% per year stability in a matter of hours with such a system or 0.01% per year stability in a matter of days. In high reliability testing programs or in basic research investigations, such capability can greatly reduce the total time to get the required information and can reduce the number of measurements that have to be made by several orders of magnitude. Savings in such programs can quickly pay for equipment such as the ESI Systemetrics console which makes such measurements possible.

We trust that this paper has stimulated your interest in a systematic approach to precision measurements and has given you some information about the equipment and techniques now available to implement such an approach. We would enjoy the opportunity to work with you as you continue to improve your measurement capability to meet the increasing demands of modern science and industry.